MRI in more detail

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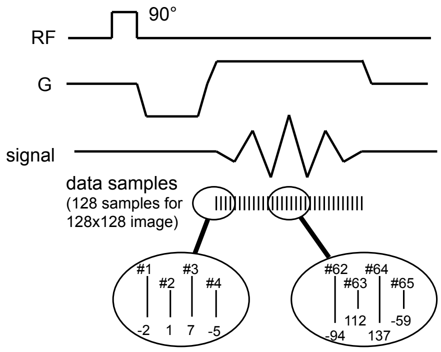
Phase encoding

- The image slice is defined using the selection gradient
- Spatial information along one direction within the slice plane is provided by the frequency encoding gradient
- Phase encoding is used to obtain spatial information along the third direction in the object under study

Phase encoding

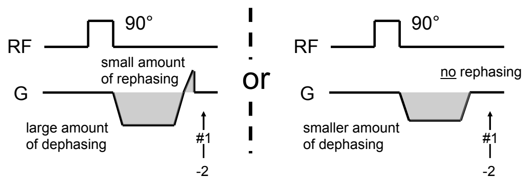
- We will see that phase encoding can be used as an alternative to frequency encoding
  - using phase encoding, we can obtain a one-dimensional projection of an object *without* observing NMR signals in the presence of a magnetic field gradient
  - (in fact, phase encoding is actually used in addition to frequency encoding)

Gradient echo pulse sequence



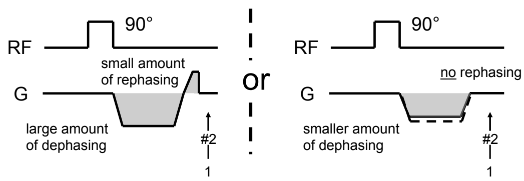
Phase encoding

- At the time of data sample #1, the magnetisation vectors have "seen":



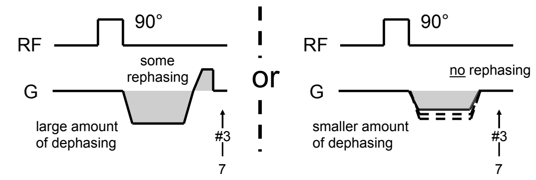
Phase encoding

- At the time of data sample #2, the magnetisation vectors have "seen":



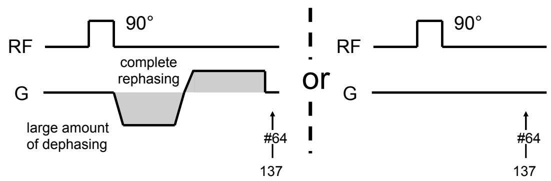
Phase encoding

- At the time of data sample #3, the magnetisation vectors have "seen":



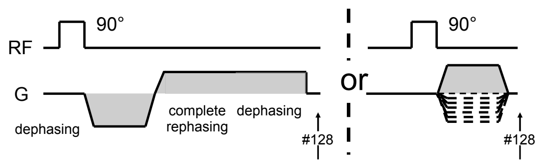
Phase encoding

- At the time of data sample #64, the magnetisation vectors have "seen":



Phase encoding

- At the time of data sample #128, the magnetisation vectors have "seen":



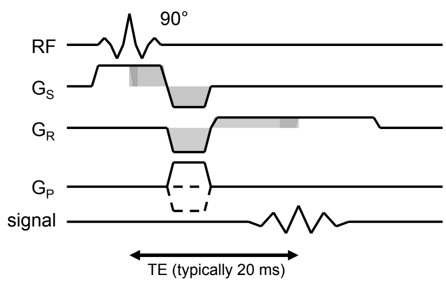
Phase encoding

- To obtain data for a one-dimensional projection of a sample:
  - in frequency encoding, apply one 90° pulse, then measure 128 samples of the gradient echo signal
  - in phase encoding, apply 128 separate 90° pulses, each one followed by a different phase-encoding gradient pulse, then take one sample of each signal

"Spin Warp" imaging

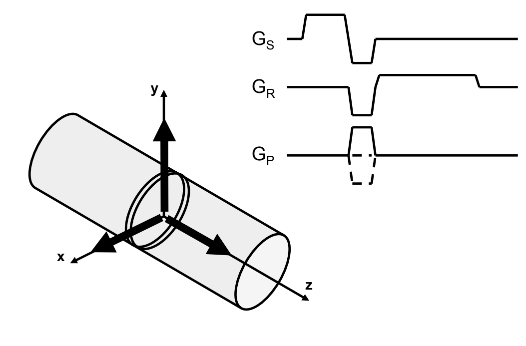
- In Spin Warp imaging, we combine the three methods:
  - selective excitation (SE)
  - frequency encoding (FE)
  - phase encoding (PE)
- The SE, FE and PE gradients are applied along orthogonal axes in space (e.g. X,Y,Z)
- Spin warp imaging is also known as 2-dimensional Fourier transform imaging (or just 2DFT)

"Spin Warp" pulse sequence

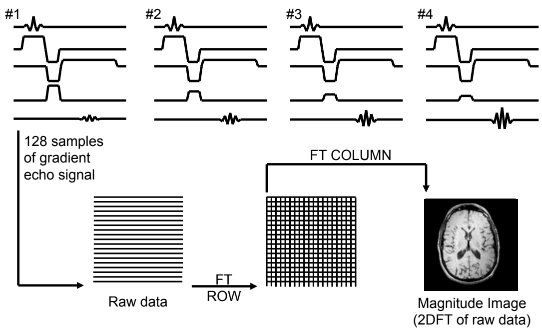


Repeated N times (for N × N image)

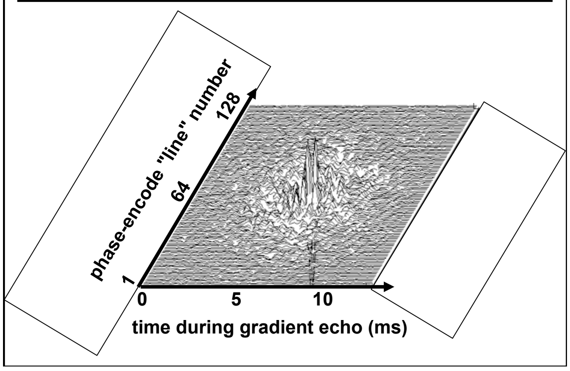
Gradient directions



2DFT image data collection



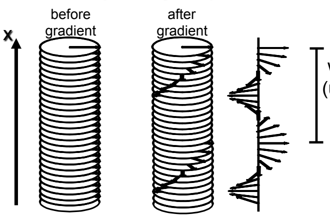
MRI raw data



k-space

"Wavenumber" k

- We can describe the dephasing effect of a gradient pulse by the "wavenumber" k
  - k is the number of wavelengths per unit distance multiplied by 2π (i.e. the rate of change of phase with distance)



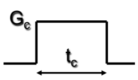
wavelength
(units: metres)

$$k = \frac{2\pi}{\lambda}$$

(units: rad m)

"Wavenumber" k

- Calculate k-number for a gradient pulse:



Change in field due to change in position Δx:	$\Delta B = \Delta x\, G_c$
Resulting change in angular frequency:	$\Delta\omega = \gamma\, \Delta x\, G_c$
Resulting change in phase over time t_c :	$\Delta\phi = \gamma\, \Delta x\, G_c\, t_c$
For one wavelength, $\Delta x = \lambda$, $\Delta\phi = 2\pi$:	$2\pi = \gamma\, \lambda\, G_c\, t_c$

$$\boxed{k = \frac{2\pi}{\lambda} = \gamma\, G_c\, t_c}$$

in general:

$$k = \gamma \int_0^T G\, dt$$

The k-vector

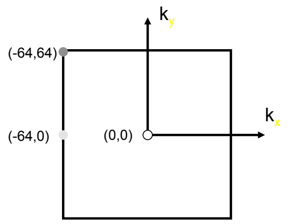
- In MRI we apply gradients in three dimensions - x, y and z
  - so we have dephasing in x, y and z
- It is useful to define "wavenumbers" in x, y and z directions: k_x, k_y and k_z
  - k_x describes dephasing in x-direction, etc.
- The k-vector is defined as

$$\underline{k} = (k_x, k_y, k_z)$$

k-space

- Different MRI pulse sequences can be characterised by the way in which they "wind up" the spins in space - i.e. by the way in which $\underline{k}$ evolves with time during the pulse sequence
- A good way of doing this is to make a two-dimensional "map" of k_x *versus* k_y, and to plot the progress of the pulse sequence on it
- This is called a "k-space map", or often just "k-space"

k-space



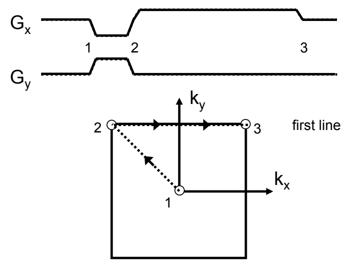
(0,0): no dephasing, spins in phase everywhere

(-64,0): large -ve dephasing along x, no dephasing along y

(-64,64): -ve dephasing along x, +ve dephasing along y

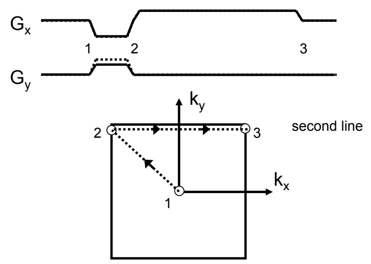
k-space trajectory

- Gradient-echo spin-warp pulse sequence
  First line:



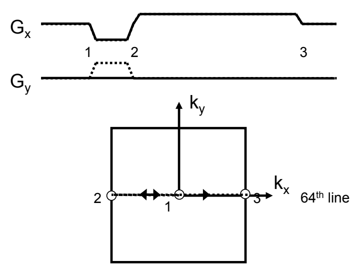
k-space trajectory of GE sequence

Second line:



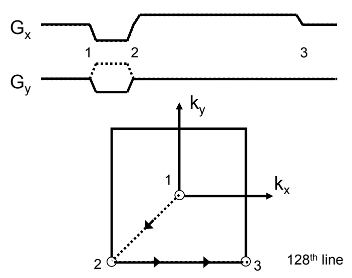
k-space trajectory of GE sequence

64th line:

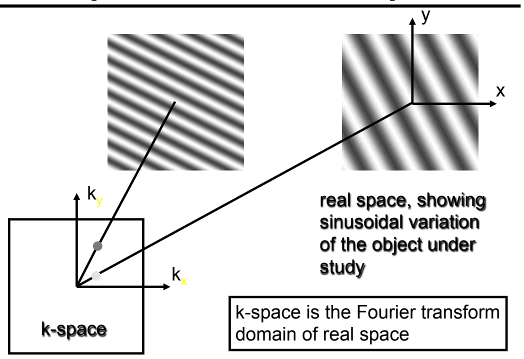


k-space trajectory of GE sequence

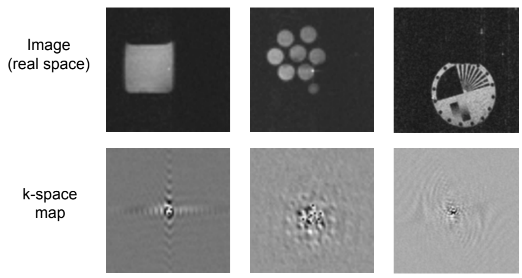
128th line:



k-space *versus* real space



k-space maps



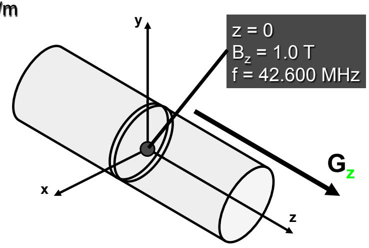
- The k-space map is just the raw MRI data!

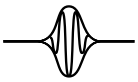
Offset slices

- To change the slice position in the body, we could move the patient
- A better method is to move the plane of the slice, along the selection direction
- This is done by using the same G_S, but applying the selective RF pulse at a higher (or lower) frequency

Offset slices

G_z = 2.35 mT/m (equivalent to 100 kHz/m)

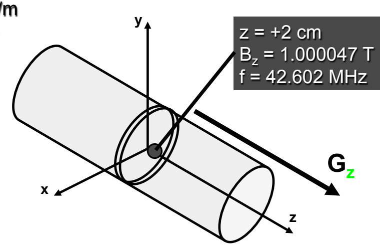


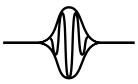


Shaped 90° RF pulse
centred on 42.600 MHz

Offset slices

G_z = 2.35 mT/m (equivalent to 100 kHz/m)



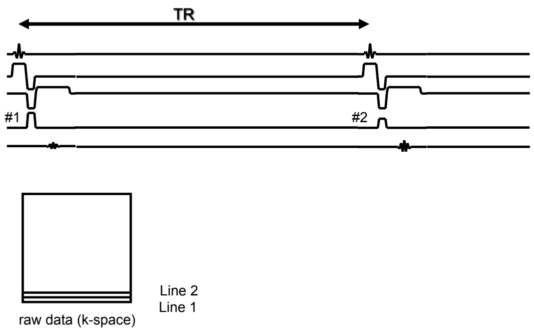


Shaped 90° RF pulse
centred on 42.6 MHz + 2 kHz = 42.602 MHz

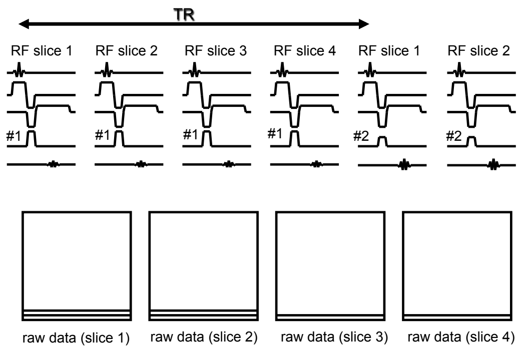
Multi-slice imaging

- Collect multiple, parallel, 2D slices
- In a normal 2D pulse sequence, data sampling takes only ~12 ms, then we wait for ~500 ms for $\mathbf{M}$ to recover before applying the next 90° pulse
- In multi-slice imaging, while we are waiting for $\mathbf{M}$ to recover in the first slice, we excite a 2nd, parallel slice (and 3rd, and 4th…)
  - parallel slices are independent of each other, so exciting one does not affect the others

Single slice



Multi-slice imaging

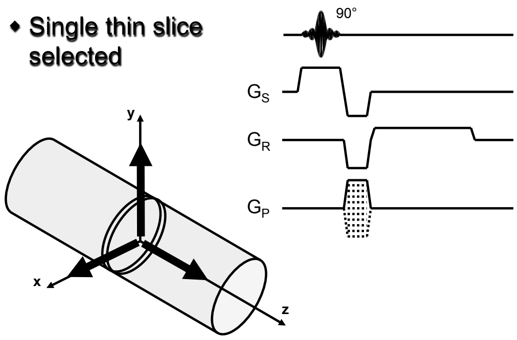


3-dimensional imaging

- The normal 2D FT pulse sequence can be modified to collect data for a three-dimensional "image"
  - e.g. to cover the whole head
- Normally have Selection, Readout and Phase-encode gradients, along z, x and y directions (for example)
- For 3D, add a second phase-encode gradient along z

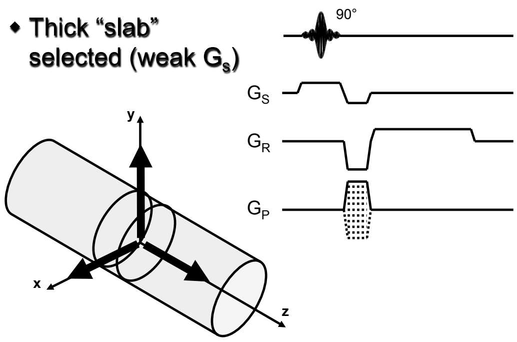
2D FT imaging

- Single thin slice selected



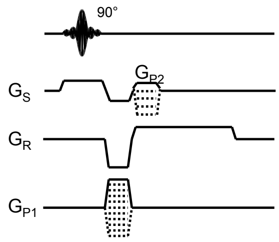
3D FT imaging

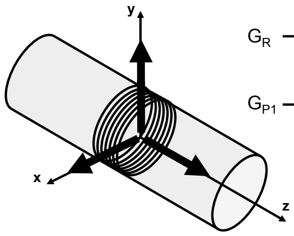
- Thick "slab" selected (weak G_s)



3D FT imaging

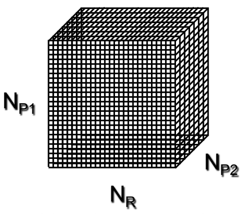
- 2nd phase-encode gradient along z





- Divides "slab" into number of "slices"

3D FT data collection



- N_R samples of each gradient echo
- N_{P1} steps of "normal" phase-encode gradient
- N_{P2} steps of second phase-encode gradient
- Need to apply $N_{P1} \times N_{P2}$ excitation pulses
  - e.g. 256 × 256 × 8 data matrix (8 "slices") requires 256 × 8 = 2048 excitations
- Perform 3D Fourier transform on data to produce 3D spatial data set